Original research

Digital twin-based bronchoscopy simulator improves training performance and skill retention of novices: a randomised controlled study

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► Additional supplemental material is published online only. To view, please visit the journal online (https://doi.org/10.1136/thorax-2025-223147).

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Received 10 February 2025
Accepted 3 October 2025

ABSTRACT

Rationale Conventional bronchoscopy training often does not ensure lasting skill retention or adaptability to different anatomies, limiting real-world impact. This study used a digital-twin bronchoscopy simulator with various CT-derived bronchial tree models to better train novices.
Objectives To explore training with various anatomically diverse bronchial tree models in novices' bronchoscopy performance.
Methods 60 bronchoscopy-naive participants were randomly assigned to three groups (n=20 each): control (written instruction only), anatomic-uniformity (trained on one standard bronchial model) and anatomic-variety (trained on multiple patient-derived bronchial models). All participants performed two tests: test 1 on a standard model and test 2 on a new CT-derived model. Both tests were repeated 3 months later to assess skill retention. The primary comparison was between the anatomic-variety and anatomic-uniformity groups.
Measurements and main results 60 participants completed tests 1 and 2. 55 returned at 3 months. In test 1, there were no significant differences between the anatomic-variety and anatomic-uniformity groups in diagnostic completeness (DC, 0 segments, p=0.576), structured progress (SP, 1 correct progression, p=0.091) and procedure time (31 s, p=0.831). In test 2, the anatomic-variety group had significantly higher DC (2.5 segments, p<0.001) and SP (9 progression, p<0.001) than the anatomic-uniformity group. At 3 months, the anatomic-variety group retained superior DC and SP scores in both tests despite slight declines.
Conclusions Training with diverse anatomical models significantly enhanced bronchoscopy performance compared with repetitive practice on a single standardised model with partially maintained learning gains at 3 months.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Simulation-based training has proven effective in facilitating learning of bronchoscopy equal to the Halstedian model of 'see one, do one, teach one'. Established simulator training provides only limited bronchial tree models and may overestimate its training effectiveness. Training with varied bronchial tree models could better simulate clinical scenarios, making this approach a potentially valuable training method.

WHAT THIS STUDY ADDS

⇒ Training on different bronchial tree models significantly improved the trainers' end-of-training bronchoscopy performance, especially on the brand-new model. Their skills were also partially maintained learning gains at 3 months.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ This study represents the first application of digital twin technology in bronchoscopy training. We created multiple bronchial tree models through this technology to better simulate clinical environments. The training programme applied in this study can be translated into clinical practice.

INTRODUCTION

The objective of flexible bronchoscopy is to navigate through the central airways and identify specific bronchial segments for accurate diagnosis and treatment of patients with lung cancer and other respiratory diseases. However, during the early stages of a trainee's learning curve, there is a lower diagnostic biopsy yield, higher complication rates and heightened patient discomfort.[1 2] These observations could be attributed to the conventional apprenticeship model, in which trainees conduct procedures under the supervision of experienced physicians. Simulation-based training, including high-fidelity and low-fidelity simulators, has proven effective in facilitating learning of bronchoscopy and can spare patients from the initial part of the trainee's learning curve.[1–4] Additionally, a standard phantom of the bronchial tree combined with an artificial intelligence (AI) system could improve novices' diagnostic completeness (DC) and structured progress (SP) scores on the bronchial tree.[5] However, a common weakness of these studies is the limited numbers of bronchial trees used in the training and final exam; more specifically, in previous simulator studies, the number of anatomical models used for training typically ranged from 1 to 6.[6 7] While simulation training on standardised models may enhance technical proficiency in controlled settings,

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To cite: Deng M, Li F, Tang F, *et al*. *Thorax* Epub ahead of print: [*please include* Day Month Year]. doi:10.1136/thorax-2025-223147

原创研究

基于数字孪生的支气管镜模拟器提升新手培训表现与技能保留：一项随机对照研究

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接收日期：2025年2月10日 接受日期：2025年10月3日

摘要

理由传统支气管镜培训往往无法确保技能的持久保留或适应不同解剖结构，限制了其在实际应用中的效果。本研究采用数字孪生支气管镜模拟器结合多种CT衍生的支气管树模型，以更有效地培训新手。**目的**探索使用解剖结构多样化的支气管树模型对新手支气管镜操作能力的培训效果。

方法60名未接受过支气管镜检查的受试者被随机分为三组（每组n=20）：对照组（仅接受书面指导）、解剖结构统一组（接受单一标准支气管模型培训）和解剖结构多样化组（接受多种患者来源支气管模型培训）。所有受试者均完成两项测试：测试1在标准模型上进行，测试2在新型CT衍生模型上进行。两项测试均在3个月后重复进行以评估技能保留情况。主要比较组别为解剖结构多样化组与解剖结构统一组。

测量数据与主要结果60名受试者完成了测试1和测试2，其中55名在3个月后返回。测试1中，解剖多样性组与解剖均匀性组在诊断完整性（DC，0个节段，p=0.576）、结构化进展（SP，1次正确进展，p=0.091）及操作时间（31秒，p=0.831）方面均无显著差异。测试2中，解剖多样性组的DC（2.5个节段，p<0.001）和SP（9次进展，p<0.001）显著高于解剖均匀性组。3个月后，尽管存在轻微下降，解剖多样性组在两项测试中仍保持更高的DC和SP评分。

结论与在单一标准化模型上重复练习相比，使用多样化解剖模型进行训练可显著提升支气管镜检查操作能力，且在3个月时仍能部分维持学习增益。

关于该主题已知信息

- 基于模拟的培训已被证实能有效促进支气管镜学习，其效果与Halstedian模型的'观察-实践-教学'原则相当。现有模拟器培训仅提供有限的支气管树模型，可能高估其培训效果。采用多样化支气管树模型的培训可更真实地模拟临床场景，使该方法成为一种潜在有价值的培训手段。

本研究的新增内容

- 在不同支气管树模型上的训练显著提高了培训者的培训结束时支气管镜检查表现，尤其在全新模型上。其技能在3个月时仍部分维持了学习收益。

本研究可能对研究、实践或政策产生的影响

- 本研究首次将数字孪生技术应用于支气管镜培训。我们通过该技术创建了多个支气管树模型，以更真实地模拟临床环境。本研究中应用的培训方案可转化为临床实践。

介绍

柔性支气管镜检查的目的是通过中央气道导航，识别特定支气管节段，以实现肺癌及其他呼吸系统疾病患者的精准诊断与治疗。然而，在培训学员的早期学习阶段，其诊断活检率较低、并发症发生率较高且患者不适感更明显。[1 2]这些现象可能归因于传统学徒制的局限性。在该模式中，受训者在经验丰富的医师监督下进行操作。基于模拟的培训（包括高仿真和低仿真模拟器）已被证明能有效促进支气管镜学习，并可使患者免于经历受训者学习曲线的初始阶段[1–4]。此外，将支气管树标准模型与人工智能（AI）系统结合，可提高新手在支气管树诊断完整性（DC）和结构化进展（SP）评分[5]。然而，这些研究的共同缺陷在于培训和最终考试中使用的支气管树数量有限；更具体而言，在先前的模拟器研究中，用于培训的解剖模型数量通常为1至6个[6 7]。虽然在标准化模型上进行模拟培训可能在受控环境中提升技术熟练度，

引用格式：Deng M，Li F，Tang F， 等 .*Thorax*电子版优先出版：[*请注明*日期（日/月/年）]. doi:10.1136/thorax-2025-223147

its ability to foster adaptability to real-world clinical complexity remains limited.[8] Conventional simulators often fail to address anatomical variability, such as congenital branching anomalies or tumour-induced airway distortions, commonly encountered in practice. Consequently, skills acquired through repetitive training on uniform models may not translate to improved bronchoscopy performance in a patient setting (Kirkpatrick levels 3–4), underscoring the need for training paradigms that bridge simulated and clinical environments.

Therefore, we developed a digital-twin bronchoscopy simulator of a patient environment. The purpose of this study was to evaluate whether training with various bronchial tree models in this digital-twin-based bronchoscopy simulator enhances novices' end-of-training bronchoscopy performance compared with the classical high-fidelity simulator. Additionally, the study aimed to determine whether this training curriculum supports the retention of bronchoscopy skills in novices 3 months post-training. Some of the results of these studies have been previously reported in the form of an abstract.[9]

METHODS

This was a multicentre randomised controlled trial conducted in a simulated environment at three centres. This trial adhered to the Consolidated Standards of Reporting Trials (CONSORT) guidelines for simulation-based studies.[10] The completed CONSORT checklist is provided, and the trial protocol is available on request.

Materials

The digital-twin-based simulator: All simulator-based operations are conducted using this device (Simulation AI plus, Zhejiang UE Medical Corp. Zhejiang, China), which comprises the following three core components. The digital-twin bronchoscopy simulator was developed through a multistage process integrating advanced imaging, AI and hardware engineering. First, over 40 000 anonymised chest CT sequences (1 mm slice thickness) were processed using a custom UV-Net deep learning model to achieve precise three-dimensional (3D) segmentation of pulmonary structures: five lung lobes with smooth boundaries, seventh-generation bronchial trees (including 18 segmental and 42 subsegmental bronchi), and differentiated arterial/venous vasculature. These segmented models were converted into interactive 3D meshes via Unity3D, enabling photorealistic rendering of both extraluminal anatomy and endoscopic views. A proprietary bronchoscope handle equipped with inertial and haptic sensors tracked real-time manoeuvres (insertion, rotation, tip articulation), synchronising movements with the virtual model.

Equipment: Bronchoscopy training was performed using a digital-twin-based bronchoscopy simulator, which consisted of an operating device for receiving simulated bronchoscopy operations from the user, a monitor for displaying a graphical interface for interaction with the user, and an AI-based feedback system containing four features: DC, SP, procedure time (PT) and wall contact time.

Screen labels: In the learning mode, the system automatically recognised bronchial segments and displayed them directly on the endoscopic image (figure 1).

Tracheobronchial tree diagram: After importing the CT image, the tracheobronchial tree diagram was automatically generated. The lung tree diagram informed the endoscope of its position in the bronchial tree during training.

The digital bronchial tree models were derived from high resolution CT (HRCT) of the chest performed for clinical indications in patients. HRCT was performed with a CT scanner (GE HiSpeed Advantage CT scanner, GE Medical Systems, Milwaukee, Wise) during a single breath-hold acquisition. Scanning parameters consisted of 2 mm X-ray beam collimation (slice thickness), 6 mm/s table speed and 1 mm reconstruction intervals. HRCT images were then transferred from the scanner to the digital-twin based bronchoscopy simulator. The system reconstructed multilayer views of the thorax and virtual bronchoscopy images. AI automatically identified anatomical structures, including 18 segmental bronchi, as well as blood vessels, nodules and other features.

DC score: The DC score tracked the segments that were entered. If the segment was correctly identified, the stage displayed the correct anatomical name and recorded a score of 1 point; otherwise, it turned grey.

SP score: The SP score tracked the segments that were entered and whether they had been entered according to the SP score. If entered in accordance with the SP score (ie, immediately following the correct preceding segment), 1 point was awarded; otherwise, no points were recorded for that segment. The system automatically recognised and ranked the process by which the participants identified the segments.[5]

Participants

Participants (medical students) were recruited from various local medical schools. The exclusion criteria included prior experience with clinical or simulated endoscopy. The sample size calculation focused on detecting differences between the anatomic-variety and anatomic-uniformity groups (primary comparison). Based on prior data,[5] group B (anatomic uniformity) had an SP score of 14±3.9. We hypothesised that group C (anatomic variety) would achieve near-perfect performance (SP=17.5±1.5).[11] Using a two-sample t-test (α=0.05, power=90%), 17 participants per group were required (total n=34). To account for potential attrition and enable three-group descriptive comparisons, we inflated the sample to 20 per group (total N=60).

Randomisation and training

The study contained two parts: training and testing. Initially, all participants watched an instructional video demonstrating the fundamental operation of the bronchoscopy simulator, which was operated and recorded by the first author. A random number table was used to allocate participants at a 1:1:1 ratio across three groups: the control group, the anatomic-uniformity group and the anatomic-variety group. Participants were additionally stratified by sex, as previous studies[12] have identified sex as a factor influencing performance during the initial skill acquisition phase (figure 2).

Anatomic-variety group: After randomisation, the anatomic-variety group watched a 4 min instructional video on how to use the digital-twin-based bronchoscopy simulator. Twenty digital bronchial tree models generated from patients' CT were used for training. After each bronchoscopy, the anatomic-variety group received a report that included the PT and visual segment checklists, such as DC and SP scores generated by the AI system.

Anatomic uniformity group: Following randomisation, the anatomic-uniformity group watched the same instructional video. Trainees were trained exclusively using a standardised digital bronchial tree model within the same simulator mentioned above. The standardised digital bronchial tree model utilised in this study was identical to that reported in a previous study.[5] After each bronchoscopy, the anatomic uniformity group also received the same report.

这类模拟器在培养适应现实临床复杂性方面仍存在局限。[8]传统模拟器往往难以应对解剖结构的变异性，例如先天性分支异常或肿瘤导致的气道扭曲等临床常见问题。因此，通过标准化模型反复训练获得的技能，可能无法有效提升患者环境下的支气管镜操作水平（柯克帕特里克分级3-4级），这凸显了建立连接模拟与临床环境的培训模式的必要性。

为此，我们开发了一款基于数字孪生技术的支气管镜模拟训练系统。本研究旨在评估：相较于传统高仿真模拟器，使用不同支气管树模型进行训练是否能提升新手在培训结束时的支气管镜操作水平。同时，研究还试图验证该训练方案能否帮助新手在培训后三个月内巩固支气管镜操作技能。部分研究成果已以摘要形式发表。[9]

方法

这是一项在三个中心模拟环境中开展的多中心随机对照试验。本试验遵循基于模拟研究的《试验报告统一标准》（CONSORT）指南。[10]已完成的CONSORT清单提供于文中，试验方案可应要求获取。

材料

基于数字孪生的模拟器：所有模拟操作均通过该设备（Simulation AI plus，浙江浙医集团，中国浙江）完成，该设备包含以下三个核心组件。数字孪生支气管镜模拟器是通过整合先进成像技术、人工智能和硬件工程的多阶段流程开发而成。首先，采用定制的UV-Net深度学习模型处理超过40,000组匿名胸部CT序列（层厚1毫米），实现肺部结构的精确三维（3D）分割：包含边界平滑的五个肺叶、第七代支气管树（含18个节段支气管和42个亚节段支气管）以及分化的动静脉血管系统。这些分割模型通过Unity3D转换为交互式3D网格，可对腔外解剖结构和内窥镜视图进行逼真渲染。配备惯性与触觉传感器的专有支气管镜手柄实时追踪操作动作（插入、旋转、尖端关节运动），并将动作与虚拟模型同步。

设备：支气管镜培训采用基于数字孪生的支气管镜模拟器完成，该设备包含：用于接收用户模拟支气管镜操作的手术装置、用于显示图形界面以供用户交互的显示器，以及基于人工智能的反馈系统，该系统包含四项功能：数字孪生（DC）、手术路径（SP）、操作时间（PT）和壁接触时间。

*屏幕标签：*在学习模式下，系统自动识别支气管节段并直接显示于内窥镜图像上（图1）。

*气管支气管树图：*导入CT图像后，
气管支气管树图被自动生成。肺树图在训练期间向内窥镜指示其在支气管树中的位置。

数字支气管树模型源自临床检查中获取的胸部高分辨率CT（HRCT）患者的适应症。 HRCT 使用CT扫描仪（GE HiSpeed Advantage CT扫描仪，GE Medical Systems，密尔沃基，威斯）在单次屏气采集期间完成。扫描参数包括2毫米X射线束准直（层厚）、6毫米/秒的扫描速度和1毫米的重建间隔。随后将 HRCT 图像从扫描仪传输至基于数字孪生的支气管镜模拟器。该系统重建了胸部的多层视图和虚拟支气管镜图像。AI自动识别了包括18个节段支气管在内的解剖结构，以及血管、结节和其他特征。

DC评分：DC评分追踪输入的解剖节段。若节段识别正确，界面将显示正确的解剖名称并记录1分；否则，该节段显示为灰色。

SP评分：SP评分追踪输入的片段，并根据SP评分判断是否符合输入要求。若输入符合SP评分（即紧接在正确前一个片段之后），则获得1分；否则，该片段不计分。系统自动识别并对参与者识别片段的过程进行排序。[5]

参与者

受试者（医学生）从当地多所医学院招募。排除标准包括既往有临床或模拟内镜检查经验。样本量计算主要针对解剖多样性组与解剖均匀性组（主要比较组）的差异检测。根据前期数据，[5]组B（解剖均匀性）的SP得分为14±3.9。我们假设C组（解剖多样性）将实现近乎完美的表现（SP=17.5±1.5）。[11]采用双样本t检验（α =0.05，检验效能=90%），每组需17名受试者（总样本量n=34）。为考虑潜在流失率并实现三组描述性比较，我们将样本量扩大至每组20人（总样本量N=60）。

随机化与培训

本研究包含培训与测试两个部分。首先，所有参与者观看了一段教学视频，该视频由第一作者操作并录制，演示了支气管镜模拟器的基本操作流程。随后采用随机数字表将参与者按1:1:1的比例分配至三个组别：对照组、解剖结构一致性组和解剖结构多样性组。此外，根据既往研究[12]中关于性别对技能习得初期表现影响的发现图2，本研究还对参与者进行了性别分层。

解剖学分组：随机分组后，解剖学分组观看了一段4分钟的指导视频，内容为如何使用基于数字孪生的支气管镜模拟器。训练中使用了20个由患者CT生成的数字支气管树模型。每次支气管镜检查后，解剖学分组会收到一份报告，其中包含由AI系统生成的PT和视觉分段检查表，例如DC和SP评分。

解剖学一致性组：随机分组后，解剖学一致性组学员观看相同教学视频。受训者仅通过上述相同模拟器中的标准化数字支气管树模型接受培训。本研究采用的标准化数字支气管树模型与先前研究报告完全一致[5]。每次支气管镜检查后，解剖学一致性组学员还会收到相同的报告。

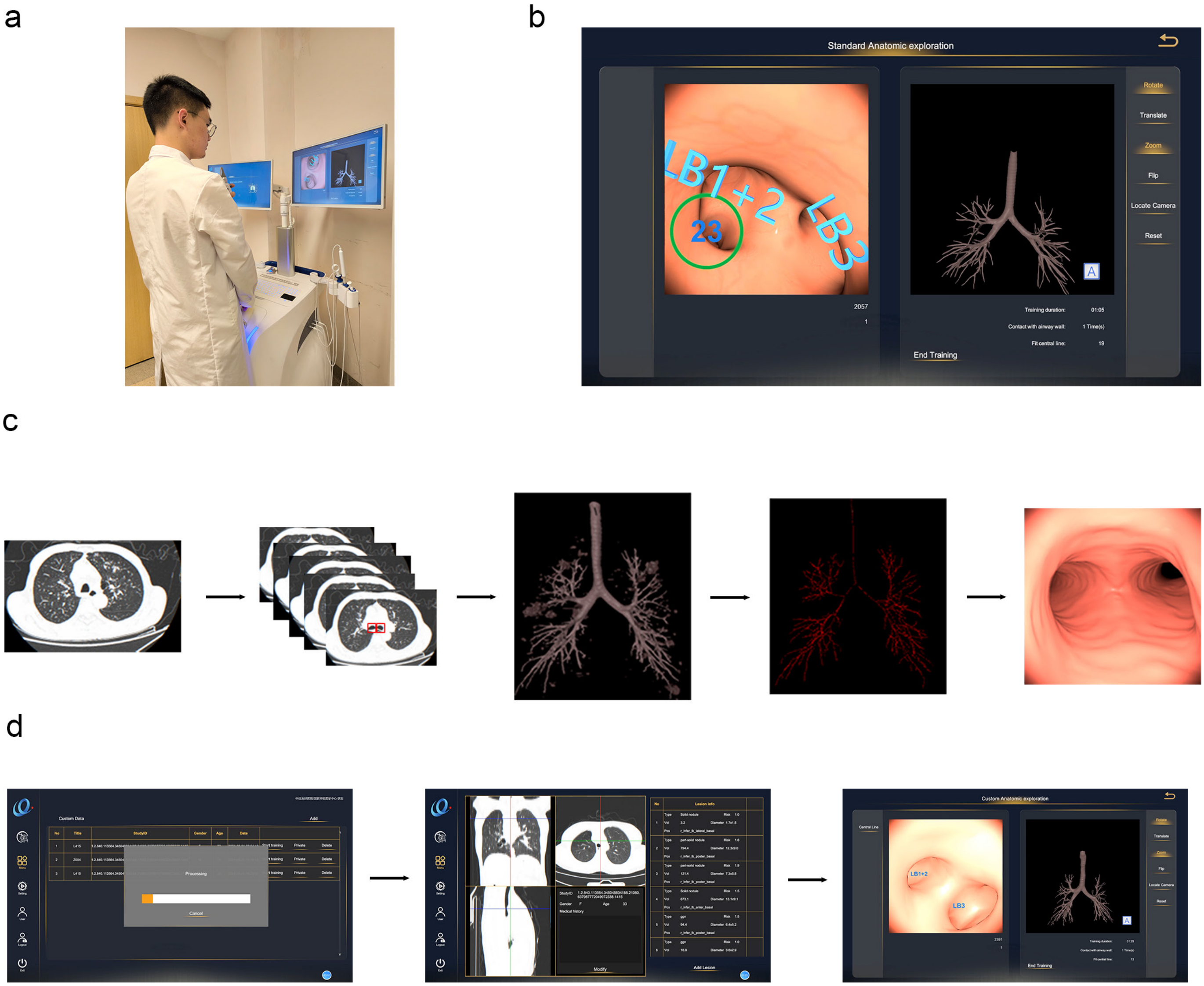

Figure 1 Simulator learning group with the studying mode activated. (a) Participant Training with the Digital-Twin Based Simulator with Artificial Intelligence Activated. (b) Onscreen tab (centre of the screen) displaying the currently visualised segment in the standard model. LB1+2/LB3. (c) Three-dimensional reconstruction of the digital bronchial tree models: 1. Image processing: The acquired CT image data underwent preprocessing, including noise reduction and enhancement operations, to improve image contrast for better visualisation of the bronchial structures. 2. Bronchial segmentation: A combination of threshold segmentation and region-growing methods was used to separate the bronchial structures from the background, forming independent bronchial structures. The segmented data were manually annotated with the anatomical names of the bronchial segments. Once sufficient data had been accumulated, a deep learning model for the automated annotation of bronchial segment names was developed. 3. Three-dimensional reconstruction: The segmentation of all cross-sectional bronchial data was completed and combined with the data layer thickness to perform overlay calculations, forming a three-dimensional (3D) mesh model of the bronchial structures. The mesh model was optimised with postprocessing steps such as detail enhancement and smoothing. 4. Centreline calculation: The vertices of the 3D mesh model were converted into point cloud data, and the central axis of the lumen was extracted based on geometric methods. The central axis data were filtered to remove abnormal branches, ensuring an approximate 2 mm spacing between each central axis point to facilitate subsequent simulation operations. 5. Simulation operations: Data from bronchoscopy handle sensors, central axis data and a 3D airway mesh model were integrated to form a physical motion system. A 3D physics engine based on collision and constraint calculations was used to determine the position and direction of the bronchoscope tip within the 3D airway model, thereby enabling the depiction of images under the bronchoscope. (d) Example of 3D reconstruction in the simulator: 1. CT import and processing. 2. Real-time patient CT display. 3. Airway reconstruction and simulation: The lung tree diagram (right panel) indicates the location of bronchoscopy exploration in the examined area. The lower right panel displays the length of training, number of wall touches and time the bronchoscope remained centred in the airway.

Control group: After randomisation, the control group was shown a 2 min instructional video that introduced them to traditional training methods based on the Four-Landmark Approach.[13] They were also given an instructional booklet explaining the training methods and a poster highlighting the methods and anatomy of the bronchial segments. The Four-Landmark Approach is an instruction on performing structured bronchoscopy that divides the bronchial tree into four landmarks and combines them with endoscopic angles.

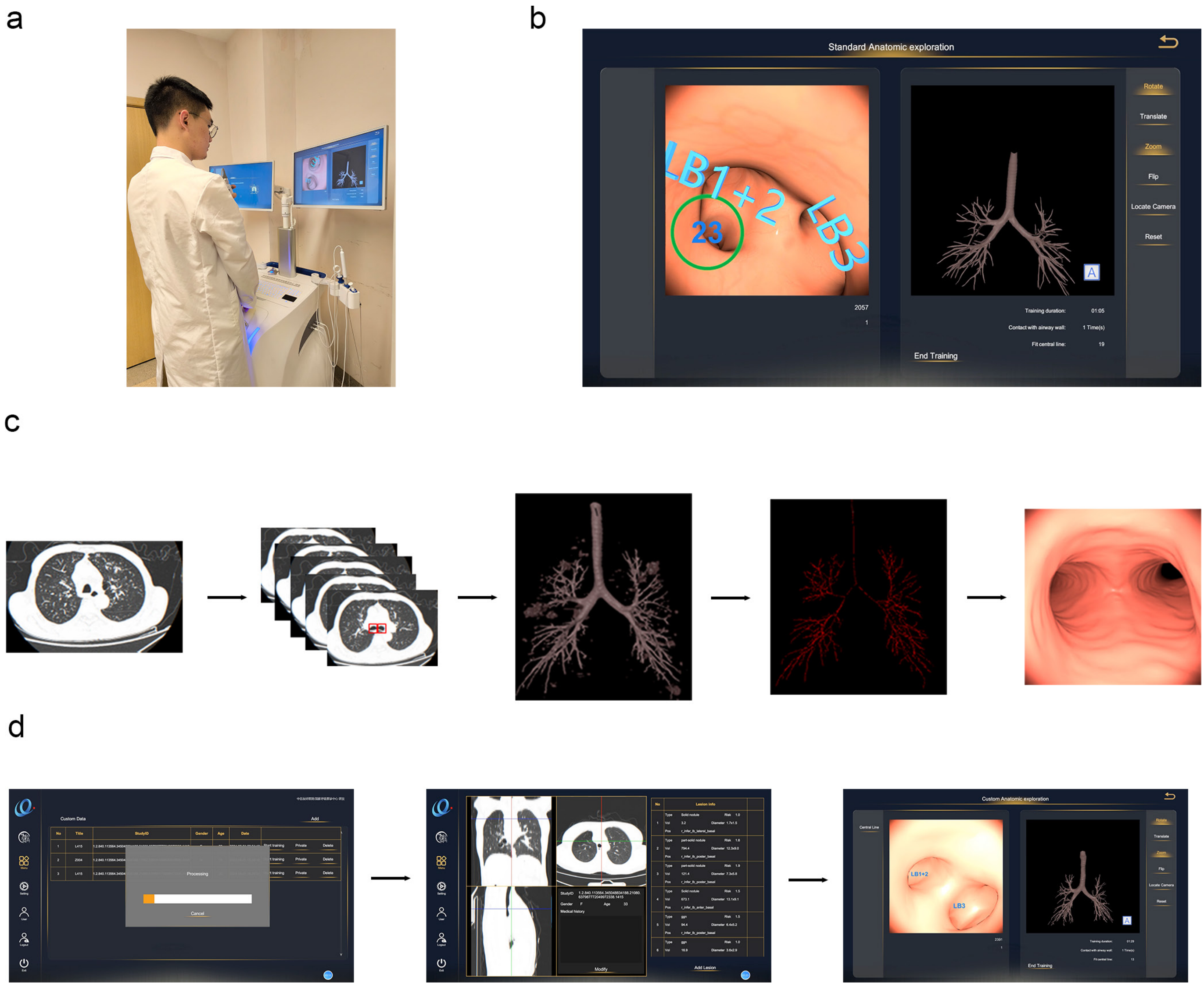

图1模拟器学习组（激活学习模式）。(a)基于数字孪生的模拟器（激活人工智能）的参与者训练。(b)屏幕中心标签页显示标准模型中当前可视化的片段。LB1+2/LB3。
(c) 数字支气管树模型的三维重建：1. 图像处理：对获取的CT图像数据进行预处理，包括降噪和增强操作，以提高图像对比度，从而更好地可视化支气管结构。2. 支气管分割：采用阈值分割与区域生长法相结合的方法，将支气管结构与背景分离，形成独立的支气管结构。对分割后的数据进行人工标注，标注支气管节段的解剖学名称。当积累足够数据后，开发了用于自动标注支气管节段名称的深度学习模型。3. 三维重建：完成所有横断面支气管数据的分割，并结合数据层厚度进行叠加计算，形成支气管结构的三维（3D）网格模型。通过细节增强和平滑等后处理步骤对网格模型进行优化。4.中心线计算：将三维网格模型的顶点转换为点云数据，并基于几何方法提取管腔中心轴。对中心轴数据进行过滤以去除异常分支，确保各中心轴点间距约2毫米，以便后续模拟操作。5. 模拟操作：将支气管镜手柄传感器数据、中心轴数据及三维气道网格模型整合形成物理运动系统。采用基于碰撞与约束计算的三维物理引擎，确定支气管镜尖端在三维气道模型中的位置与方向，从而实现支气管镜下图像的呈现。(d)模拟器中三维重建示例：1. CT导入与处理。2. 实时患者CT显示。3. 气道重建与模拟：肺树图（右图）显示支气管镜在检查区域的探查位置。右下图显示训练时长、壁面接触次数及支气管镜在气道中保持居中的时间。

对照组：随机分组后，对照组观看了一段2分钟的指导视频，该视频向他们介绍了基于FourLandmark方法的传统训练方法[13]。同时，他们还收到了一本解释训练方法的指导手册和一张海报。

重点阐述支气管节段的解剖学方法。四标志法是一种结构化支气管镜检查的操作指南，该方法将支气管树划分为四个标志点，并结合内镜角度进行定位。

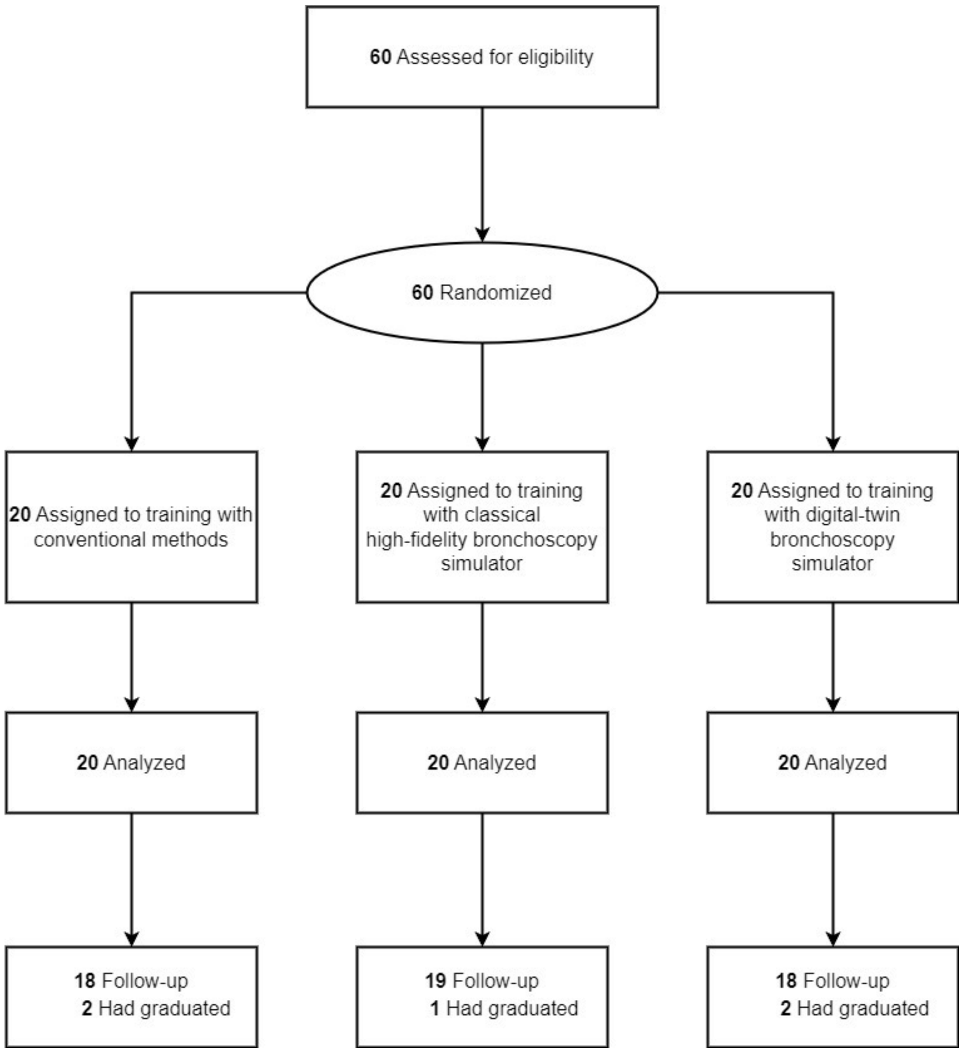

Figure 2 Participant flow diagram. A detailed diagram illustrating the progression of participants throughout the trial.

Training: Participants were allowed unrestricted training time but were constrained to a maximum of 3.5 hours to prevent fatigue during testing. Participants were permitted unrestricted training time to reflect typical clinical learning environments. While mastery learning—a gold standard requiring predefined competency benchmarks—was not employed here, this design choice allowed us to examine naturalistic skill acquisition patterns and trainee self-assessment accuracy.

Test

When the participants no longer felt that they had benefited from the additional training, they took the final test, which was a complete bronchoscopy, with no guidance or assistance. The final test was the same for all groups, with no use of a feedback tool. It involved two tests: Test 1 was a standard digital bronchial tree model (the model once used in the training of the anatomic-uniformity group), and test 2 was a digital bronchial tree model based on a brand-new chest CT. The test could only be performed once, after which the user interface was locked, and the test ended. The system automatically timed the test, starting when the bronchoscope entered the airway and ending when the bronchoscope completely exited the airway.

After the test, all groups completed the Intrinsic Motivation Inventory (IMI) questionnaire.[5] The questionnaire comprised six statements. Each statement was rated using a Likert scale from 1 to 7, with 1 indicating ‘not at all true’ and 7 indicating ‘very true’.

Skill maintenance: 3 months after training, participants repeated the same testing protocol to assess knowledge retention; this involved a standard and a brand-new digital bronchial tree model with the following measures: DC, SP and PTs.

Outcome measures

All participants were informed that they were required to achieve the highest possible score on the examination:

DC: DC was defined as probing and recognising all bronchial segments, with a total of 18 segments: 10 in the right lung and 8 in the left lung; left lungs one and two were fused, and no segment 7.[3 14]

SP: A point was awarded each time a participant moved from one segment to the next.[15] For example, exploring the right upper lobe in the following order: a sequence of trachea/right bronchial segment RB1/RB2/RB3 earned three points, while a sequence of trachea/RB2/RB1/RB3 earned 0 points.

PT: PT was defined as the time spent visualising the carina to extract the scope.[3 14] AI automatically timed the operational process.

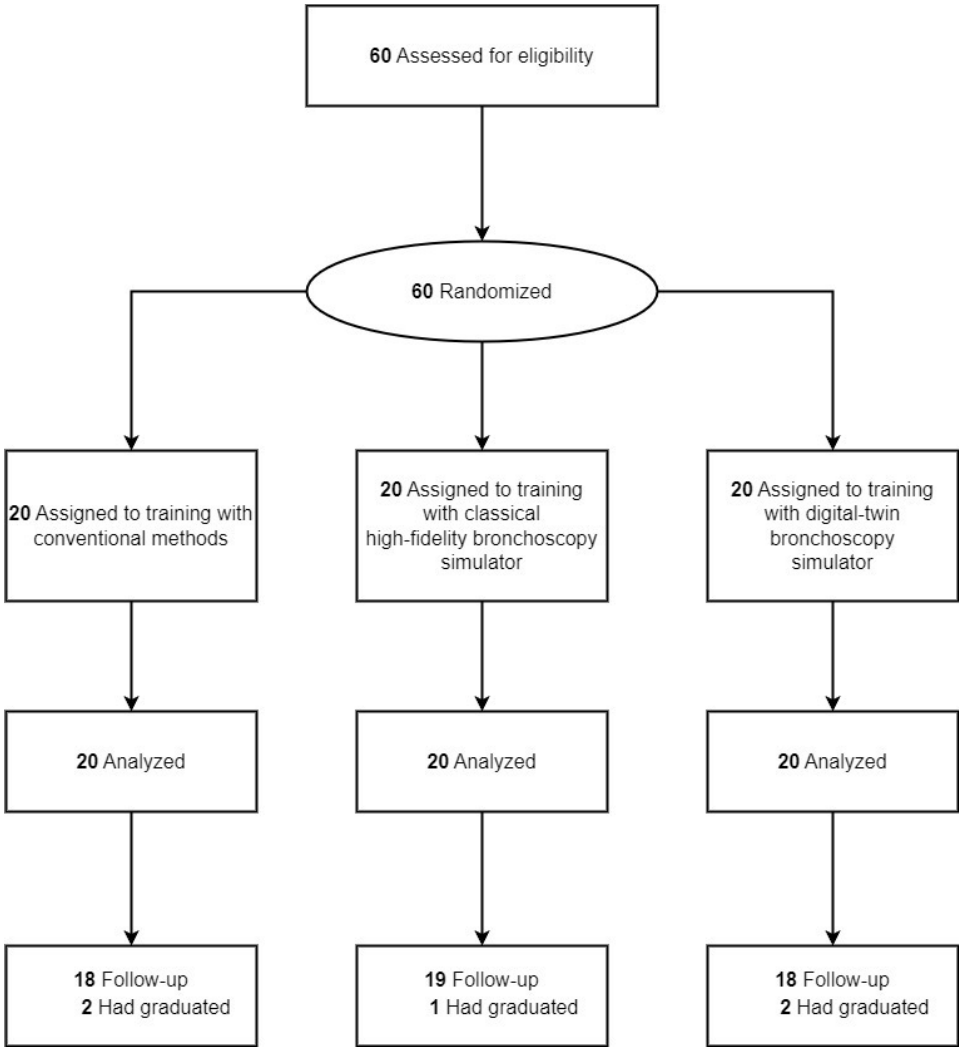

图2 受试者流程图。详细展示受试者在整个试验期间的进程示意图。

训练：受试者可进行不受限制的训练，但为防止测试期间疲劳，训练时间上限为3.5小时。允许不受限制的训练时间以反映典型的临床学习环境。虽然本研究未采用需要预设能力基准的黄金标准——掌握学习法，但这一设计选择使我们能够考察自然技能习得模式及受训者自我评估准确性。

试验

当受试者不再认为从额外培训中获益时，他们将接受最终测试——即在无任何引导或辅助的情况下完成一次完整的支气管镜检查。所有组别的最终测试均相同，且不使用反馈工具。该测试包含两项内容：测试1为标准数字支气管树模型（即解剖学一致性组培训曾使用过的模型），测试2则基于全新胸部CT生成的数字支气管树模型。测试仅允许执行一次，之后用户界面将被锁定并终止测试。系统会自动计时测试，从支气管镜进入气道开始计时，至支气管镜完全退出气道时结束。

测试结束后，所有组别均完成了内在动机量表（IMI）问卷。[5]该问卷包含六条陈述，每条陈述均采用评分标准进行评估。采用1至7分的李克特量表，其中1分表示‘完全不符合’，7分表示‘非常符合’。

技能维持：培训结束后3个月，受试者重复相同的测试方案以评估知识保留情况；该方案包括标准数字支气管树模型和全新数字支气管树模型，并采用以下测量指标：DC、SP和PTs。

结局指标

所有受试者均被告知需在检查中取得最高可能分数：

DC：DC定义为探查并识别所有支气管节段，共计18个节段：右肺10个，左肺8个；左肺第一、二肺融合，无第7节段。[3,14]

SP：每次参与者从一个节段移动到下一个节段时，可获得1分。[15]例如，按以下顺序探索右肺上叶：气管/右支气管节段RB1/RB2/RB3的序列可获得3分，而气管/RB2/RB1/RB3的序列则得0分。

PT：PT定义为通过观察隆突以取出内窥镜所花费的时间。[3,14] AI自动计时该操作流程。

Statistical analysis

The ceiling effect and the fact that DC and SP have a maximum score of 18 could make normal distribution infeasible. Consequently, data for DC, SP, PT and training duration are presented as median±IQR, and non-parametric Kruskal-Wallis tests were employed for group comparisons. The χ^2 test was used for categorical variables. The primary analysis compared the anatomic-variety group with the anatomic-uniformity group. All other comparisons were considered secondary analyses. For the primary comparison, the Kruskal-Wallis test was applied. To compare all three groups across DC, SP and PT, Kruskal-Wallis tests were used. When a globally significant difference was detected ($p<0.05$), Dunn's test with Bonferroni correction was used for post hoc pairwise comparisons. Effect sizes were calculated as rank eta squared (ηH^2). For comparisons between groups (ie, anatomic-variety group vs anatomic-uniformity group), effect sizes were calculated using the rank-biserial correlation (r_b). The r_b was interpreted as follows: 0.1=small, 0.3=medium, 0.5=large. Given the bounded, non-normal distribution of the DC and SP scores, a Scheirer-Ray-Hare test (rank-based two-way analysis of variance) was used to evaluate the effects of group and time (post-test vs 3-month retention) and their interaction. Between-group differences are reported as median differences and p values. Statistical significance was set at $p<0.05$.

RESULTS

The digital-twin bronchoscopy simulator of a patient environment that could reconstruct digital bronchial trees generated from diverse patient chest CT data and automatically identify bronchial segments based on AI. This simulator not only mimics the experience of bronchoscopy in a real clinical setting by providing various anatomic models but also provides immediate AI-based training feedback. Training with an extensive range of digital bronchial tree models generated from CT data of various patients closely simulates clinical practice.

In this prospective, randomised controlled trial conducted from 1 June 2024 to 28 September 2024, 60 participants were enrolled, and 20 participants were allocated to each group (table 1).

Post-test

In test 1, the primary comparison showed that there were no significant differences between the anatomic-variety and anatomic-uniformity groups in the three outcomes (median difference, p value): DC (0 segments, $p=0.576$), SP (1 correct progressions, $p=0.091$) and PT (31 s, $p=0.831$). Secondary analyses revealed that both groups exhibited superior training performance compared with the control group, as indicated by the three outcomes (median, p value): DC (18, 18, 13.5 segments, $p<0.001$, $\eta H^2=0.627$), SP (17, 16, 8.5 correct progressions, $p<0.001$, $\eta H^2=0.596$) and PT (475, 444, 913.5 s, $p<0.001$, $\eta H^2=0.416$).

In test 2, the primary comparison demonstrated the anatomic-variety group had significantly higher DC (median difference: 2.5 segments, $p<0.001$, $r_b=0.945$) and SP (median difference: 9 progression, $p<0.001$, $r_b=0.995$) than the anatomic-uniformity group. It is noteworthy that there was no significant difference in PT between the two groups (see table 1). Secondary analyses revealed that both the anatomic-variety and anatomic-uniformity groups demonstrated superior training performance in comparison to the control group (table 1).

Additionally, to evaluate the stability of the bronchoscopy performance for each group, we compared the outcomes in two tests. The anatomic-variety group demonstrated more stable performance in both the DC and SP scores: DC (median difference: –0.5 points, $p=0.257$) and SP (0 correct progressions, $p=0.796$). However, the anatomic-uniformity group showed an unstable performance in both DC and SP: DC (–3 points, $p<0.001$, $r_b=-0.78$) and SP (–8 correct progressions, $p<0.001$, $r_b=-1.0$). The PTs were prolonged in both the anatomic-variety (221 s, $p<0.001$, $r_b=0.488$) and anatomic-uniformity groups (346 s, $p<0.001$, $r_b=0.607$). In the control group, the performance was also unstable in both the DC and SP, but the PTs showed no significant change between the two tests.

The training time across the three groups was comparable, but the participants using the digital-twin simulator had higher IMI scores than the control group (18.5 scores, $p<0.001$, $r_b=0.539$) (table 2).

Table 1 Participants' demographic and outcome measures

	Control group (group A, N=20)	Anatomic-uniformity group (group B, N=20)	Anatomic-variety group (group C, N=20)	P value (group A vs B vs C)	P value (group B vs C)
Female sex*	10 (50%)	10 (50%)	10 (50%)	1	1
Age, years	24.3 (0.44)	24.6 (0.57)	24.0 (0.00)	0.640	0.429
Testing with the trained standard digital bronchial tree model					
DC, segments	13.5 (2.5)	18 (2)	18 (1)	< 0.001	0.576
SP, progressions	8.5 (5.5)	16 (3)	17.0 (2.5)	< 0.001	0.091
PT, s	913.5 (249.0)	444 (251.5)	475.0 (268)	< 0.001	0.831
Testing with a digital bronchial tree generated from a brand-new chest CT					
DC, segments	7.0 (4)	15 (2)	17.5 (1)	<0.001	<0.001
SP, progression, s	3.5 (3)	8 (2.5)	17 (1.50)	<0.001	<0.001
PT, s	1007.5 (473.50)	790 (331.50)	696.0 (258)	0.001	0.475
Time spent training, min	55 (29.50)	60 (35)	60 (15.50)	0.842	0.936

Data are presented as median (IQR) and were compared using the Kruskal-Wallis test.
*Data are presented as numbers (percentage) and were compared using the χ^2 test. Statistical significance was set at $p<0.05$.
DC, diagnostic completeness; PT, procedure time; SP, structured progress.

统计分析

天花板效应以及DC和SP的最大分值为18这一事实，可能使得正态分布难以实现。因此，DC、SP、PT及训练时长的数据均以中位数± IQR 表示，并采用非参数Kruskal-Wallis检验进行组间比较。分类变量使用 χ^2检验。主要分析比较解剖多样性组与解剖均匀性组，其余比较均视为次要分析。主要比较采用Kruskal-Wallis 检验，而DC、SP和PT三组间的比较则使用Kruskal-Wallis检验。当检测到全局显著差异（p<0.05）时，采用Dunn检验结合Bonferroni校正进行事后两两比较。效应量计算采用秩η^2（ηH2），组间比较（即解剖多样性组与解剖均匀性组）则使用秩-二列相关（rb）。r_b的解释标准如下：0.1=小效应，0.3=中等效应，0.5=大效应。鉴于DC和SP评分呈有界非正态分布，采用Scheirer-Ray-Hare检验（基于秩次的双向方差分析）评估组别与时间（后测 vs 3个月保留期）及其交互作用的影响。组间差异以中位数差值及p值报告。统计学显著性设定为p<0.05。

结果

这款数字孪生支气管镜模拟器能够重建基于不同患者胸部CT数据生成的数字支气管树，并通过人工智能自动识别支气管节段。该模拟器不仅通过提供多种解剖模型模拟真实临床环境中的支气管镜检查体验，还能即时提供基于人工智能的培训反馈。通过使用由不同患者CT数据生成的广泛数字支气管树模型进行训练，可高度模拟临床实践。

在这项2024年6月1日至2024年9月28日开展的前瞻性随机对照试验中，共纳入60名受试者，每组分配20名受试者（表1）。

测试后

在测试1中，主要比较显示解剖多样性组与解剖均匀性组在三个结果指标（中位数差异，p值）上无显著差异：DC（0节段，p=0.576）、SP（1次正确进展，p=0.091）和PT（31秒，p=0.831）。次要分析表明，两组均表现出优于对照组的训练表现，具体体现在三个结果指标（中位数，p值）上：DC（18、18、13.5节段，p<0.001，ηH^2=0.627）、SP（17、16、8.5次正确进展，p<0.001，ηH^2=0.596）和PT（475、444、913.5秒，p<0.001，ηH^2=0.416）。

在测试2中，主要比较结果显示解剖多样性组的DC（中位差值：2.5节段，p<0.001，r_b=0.945）和SP（中位差值：9节段，p<0.001，r_b=0.995）显著高于解剖均匀性组。值得注意的是，两组间的PT无显著差异（参见表1）。次要分析表明，与对照组相比，解剖多样性组和解剖均匀性组均表现出更优的训练表现（表1）。

此外，为评估各组支气管镜检查操作的稳定性，我们比较了两项测试的结果。解剖多样性组在DC和SP评分中均表现出更稳定的操作：DC（中位差值：-0.5分，p=0.257）和SP（0次正确进展，p=0.796）。然而，解剖均匀性组在DC和SP中均显示不稳定操作：DC（-3分，p<0.001，r_b=−0.78）和SP（-8次正确进展，p<0.001，r_b=−1.0）。解剖多样性组（221秒，p<0.001，r_b=0.488）和解剖均匀性组（346秒，p<0.001，r_b=0.607）的PT均延长。对照组在DC和SP中也表现出不稳定操作，但两次测试间的PT未显示显著变化。

三组的训练时间相当，但使用数字孪生模拟器的受试者比对照组的IMI评分更高（18.5分，p<0.001，r_b=0.539）（表2）。

表1 受试者人口统计学特征与结局指标

	对照组（A组，N=20）	解剖学一致性组（B组，N=20）	解剖变异组（C组，N=20）	P值（A组 vs B组 vs C组）	P值（B组 vs C组）
女性性别*	10 (50%)	10 (50%)	10 (50%)	1	1
年龄，岁	24.3 (0.44)	24.6 (0.57)	24.0 (0.00)	0.640	0.429
使用训练完成的标准数字支气管树模型进行测试					
DC，节段	13.5 (2.5)	18 (2)	18 (1)	< 0.001	0.576
SP，进展	8.5 (5.5)	16 (3)	17.0 (2.5)	< 0.001	0.091
PT, s	913.5 (249.0)	444 (251.5)	475.0 (268)	< 0.001	0.831
使用全新胸部CT生成的数字支气管树进行测试					
DC，节段	7.0 (4)	15 (2)	17.5 (1)	<0.001	<0.001
SP，进展，s	3.5 (3)	8 (2.5)	17 (1.50)	<0.001	<0.001
PT, s	1007.5 (473.50)	790 (331.50)	696.0 (258)	0.001	0.475
训练时间，分钟	55 (29.50)	60 (35)	60 (15.50)	0.842	0.936

数据以中位数（IQR）表示，并采用Kruskal-Wallis检验进行比较。
*数据以数字（百分比）形式呈现，并采用 χ^2检验进行比较。统计学显著性设定为p<0.05。DC：诊断完整性；PT：操作时间；SP：结构化进展。

Table 2 Intrinsic Motivation Inventory (IMI)

	Control group (group A, N=20)	Anatomic-uniformity group (group B, N=20)	Anatomic-variety group (group C, N=20)	P value (group A vs B vs C)
I put a lot of effort into this	5 (2)	5 (1)	5.5 (1)	0.031
I think I did pretty well at the final test, compared with the other students	3 (2)	4 (1.5)	5 (2)	0.001
I felt pressured while training*	3.5 (5)	3 (2)	3 (2)	0.793
I think this training session is important to do because it can help me to perform better bronchoscopies	2 (1.5)	7 (1)	7 (1)	<0.001
I would recommend others to train their skills with this system	1 (1)	6.5 (1)	7 (1)	<0.001
I would like to continue to use this training system	1.5 (2)	7 (1)	7 (1)	<0.001
IMI total (total=35)	12(16)	28.5 (4)	30.50(4)	<0.001

Data are presented as median (IQR) and were compared using the Kruskal-Wallis test.
Each statement was rated using a Likert scale from 1 to 7, where one indicated 'not at all true' and seven indicated 'very true'. Number 7 indicates the best score, except for a, because it is a reverse-coded statement in which 1 indicates the best score and 7 the worst score.
*This was not included in the total IMI score.

Skill maintenance

55 of 60 (91.67%) participants returned for the bronchoscopy skill retention test. In test 1, the anatomic-variety group showed better performance maintenance than the other groups in the two outcome measures (median, p value: DC: 17, 17, 12 segments, $p<0.001$, $\eta H^2=0.462$; SP: 15, 7, 6 correct progressions, $p<0.001$, $\eta H^2=0.528$). Among the three groups, there was a trend toward a decrease in test 1 over time. Although a statistically significant difference was seen in SP scores among the groups (anatomic-variety group, $p<0.01$, $r_b=-0.556$; anatomic-uniformity group, $p<0.001$, $r_b=-0.895$; control group, $p<0.05$, $r_b=-0.406$), neither the anatomic-variety group nor the anatomic-uniformity group had significant changes in DC scores. In Test 2, the anatomic-variety group still had the best performance among the groups (DC, 17, 14, 6 segments, $p<0.001$, $\eta H^2=0.365$; SP, 13, 4, 3 correct progressions, $p<0.001$, $\eta H^2=0.738$). The three groups showed no differences in the PT for the retention test (table 3). Both the anatomic-variety and anatomic-uniformity groups showed a statistically significant difference (DC: anatomic-variety group, $p=0.008$, $r_b=-0.364$; anatomic-uniformity group, $p=0.010$, $r_b=-0.645$; control group, $p=0.068$; SP: anatomic-variety group, $p=0.001$, $r_b=-0.593$; anatomic-uniformity group, $p=0.007$, $r_b=-0.548$; control group, $p=0.060$) over time.

To investigate whether the learning gains remained stable over time, a non-parametric repeated measures Scheirer-Ray-Hare test was applied to evaluate within-group changes over time (post-test vs 3-month retention) and between-group differences (table 4). A main effect of group was seen for all measures. Additionally, a main effect of the test was found for 'SP' in test 1 and 'DC and SP' in test 2, indicating that the performance score for these measures deteriorated from post-test to retention test. However, no interaction was found between the three groups for these measures, so the deterioration in performance was found in all three groups.

DISCUSSION

To our knowledge, this is the first study to use a digital-twin bronchoscopy simulator to train and test novice bronchoscopy performance. Our results indicate that the 'anatomic-variety' training approach promoted better, faster and more stable bronchoscopy performance for novices, regardless of whether the standard or brand-new digital bronchial tree models are used. Importantly, the anatomic-variety group demonstrated partial retention of learning gains when reassessed at 3 months, as evidenced by DC and SP scores, as well as PT. However, these gains declined in the absence of repeated exposure to simulation.

Previous studies[3 16 17] have demonstrated that simulation-based training (based on virtual reality simulators or a standard phantom of the bronchial tree) combined with feedback can improve the DC and SP scores of novices, which is consistent with our study findings. In our study, the participants who used the digital-twin-based bronchoscopy simulator with AI

Table 3 Outcome measures of skill maintenance

	Control group (group A, N=20)	Anatomic-uniformity group (group B, N=20)	Anatomic-variety group (group C, N=20)	P value (group A vs B vs C)	P value (group B vs C)
Testing with the trained standard digital bronchial tree model					
DC, segments	12(3)	17±3	17(1)	<0.001	0.214
SP, progressions	6 (2)	7±4	15(6)	<0.001	<0.001
PT, s	731(203)	632(248)	604(227)	0.056	0.504
Testing with a digital bronchial tree generated from a brand-new chest CT					
DC, segments	6 (2)	14(2)	17(3)	<0.001	<0.001
SP, progressions	3 (4)	4 (4)	13(5)	<0.001	<0.001
PT, s	900 (322)	877 (375)	741 (340)	0.326	0.261

Data are presented as median (IQR) and were compared using the Kruskal-Wallis test.
Statistical significance was set at p<0.05.
DC, diagnostic completeness; PT, procedure time; SP, structured progress.

表2 内在动机量表

	对照组（A组，N=20）	解剖学一致性组（B组，N=20）	解剖变异组（C组，N=20）	P值（A组 vs B组 vs C组）
我为此付出了很多努力	5 (2)	5 (1)	5.5 (1)	0.031
与其他学生相比，我觉得自己在期末考试中表现得相当不错。	3 (2)	4 (1.5)	5 (2)	0.001
训练时感到压力*	3.5 (5)	3 (2)	3 (2)	0.793
我认为开展本次培训至关重要，因其有助于提升我的支气管镜检查操作水平。	2 (1.5)	7 (1)	7 (1)	<0.001
我建议他人通过该系统进行技能培训	1(1)	6.5 (1)	7 (1)	<0.001
本人愿意继续使用该培训系统	1.5(2)	7 (1)	7 (1)	<0.001
IMI总和（总和=35）	12(16)	28.5 (4)	30.50(4)	<0.001

数据以中位数（IQR）表示，并采用Kruskal-Wallis检验进行比较。
每条陈述均采用1至7分的李克特量表进行评分，其中1分表示“完全不正确”，7分表示“非常正确”。除a条陈述外，其余条目均以7分表示最佳评分，因为该陈述采用反向编码，即1分表示最佳评分，7分表示最差评分。
*该指标未纳入IMI总分计算。

技能维护

60名参与者中有55名（91.67%）返回进行了支气管镜技能保留测试。在测试1中，解剖多样性组在两项结果指标上均表现出优于其他组的表现维持（中位数，p值：DC：17、17、12个节段，p<0.001，ηH^2=0.462；SP：15、7、6次正确进展，p<0.001，ηH^2=0.528）。三组中，测试1随时间推移呈现下降趋势。尽管组间SP评分存在统计学显著差异（解剖多样性组，p<0.01，r_b=−0.556；解剖均匀性组，p<0.001，r_b=−0.895；对照组，p<0.05，r_b=−0.406），但解剖多样性组与解剖均匀性组的DC评分均未出现显著变化。测试2中，解剖多样性组仍保持最佳表现（DC：17、14、6个节段，p<0.001，ηH^2=0.365；SP：13、4、3次正确进展，p<0.001，ηH^2=0.738）。三组在保留测试的PT方面无差异（表3）。解剖多样性组与解剖均匀性组均显示出统计学显著差异（DC：解剖多样性组，p=0.008，r_b=−0.364；解剖均匀性组，p=0.010，r_b=−0.645；对照组，p=0.068；SP：解剖多样性组，p=0.001，r_b=−0.593；解剖均匀性组，p=0.007，r_b=−0.548；对照组，p=0.060）随时间推移。

为探究学习收益是否随时间保持稳定，采用非参数重复测量Scheirer-Ray-Hare检验评估组内随时间的变化（后测与3个月保留测试对比）及组间差异（表4）。所有测量指标均呈现组别主效应。此外，测试1中‘SP’和测试2中‘DC与SP’均存在测试主效应，表明这些指标的绩效分数从后测到保留测试呈现下降趋势。然而，这三个组别在这些指标上未发现交互作用，因此绩效下降现象在所有三个组别中均存在。

讨论

据我们所知，这是首个采用数字孪生支气管镜模拟器训练和测试新手支气管镜操作的研究。我们的结果表明，无论使用标准还是全新数字支气管树模型，‘解剖多样性’训练方法都能促进新手获得更好、更快且更稳定的支气管镜操作表现。重要的是，解剖多样性组在3个月后通过DC和SP评分以及PT评估显示，其学习成果部分得以保留。然而，若缺乏重复模拟训练，这些进步会逐渐消退。

既往研究[3 16 17]已证实，基于虚拟现实模拟器或支气管树标准体模的模拟训练结合反馈可提高新手的DC和SP评分，这与本研究结果一致。在本研究中，使用基于数字孪生的支气管镜模拟器（配备AI）的参与者

表3 技能维持的结局指标

	对照组（A组，N=20）	解剖学一致性组（B组，N=20）	解剖变异组（C组，N=20）	P值（A组 vs B组 vs C组）	P值（B组 vs C组）
使用训练完成的标准数字支气管树模型进行测试					
DC，节段	12(3)	17±3	17(1)	<0.001	0.214
SP，进展	6 (2)	7±4	15(6)	<0.001	<0.001
PT, s	731(203)	632(248)	604(227)	0.056	0.504
数字测试　由...生成的支气管树　全新胸部CT					
DC，节段	6 (2)	14(2)	17(3)	<0.001	<0.001
SP，进展	3 (4)	4 (4)	13(5)	<0.001	<0.001
PT, s	900 (322)	877 (375)	741 (340)	0.326	0.261

数据以中位数（IQR）表示，并采用Kruskal-Wallis检验进行比较。统计学显著性设定为p<0.05。
DC，诊断完整性；PT，操作时间；SP，结构化进展。

Table 4 Statistical data from repeated measures Scheirer-Ray-Hare test on the measures from the post-test and the retention test

	Test group interaction	Group main effect	Test main effect
Testing with the trained standard digital bronchial tree model			
DC, segments	H=0.233, p=0.89	H=60.62, p<0.001*	H=3.499, p=0.061
SP, progressions	H=4.30, p=0.12	H=51.99, p<0.001*	H=20.64, p<0.001*
PT, s	H=7.47, p=0.02*	H=32.36, p<0.001*	H=0.86, p=0.350
Testing with a digital bronchial tree generated from a brand-new chest CT			
DC, segments	H=0.32, p=0.85	H=84.05, p<0.001*	H=4.92, p=0.030*
SP, progressions	H=0.24, p=0.89	H=69.62, p<0.001*	H=7.56, p=0.010*
PT, s	H=3.04, p=0.22	H=13.34, p=0.001*	H=0.72, p=0.400

*Statistical significance was set at p<0.05.
DC, diagnostic completeness; PT, procedure time; SP, structured progress.

feedback performed significantly better in terms of DC, SP and PT compared with the control group during standard digital bronchial tree model tests. In contrast to previous studies,[5] we found that novices trained using a standard digital bronchial tree model, such as the classical high-fidelity simulator, showed a reduction in bronchoscopy performance when confronted with another new digital bronchial tree model test. These results suggest that the training effectiveness of the classical simulator is overestimated because it may not lead to stability in bronchoscopy performance. Schmidt and Bjork[18] demonstrated that variable practice—exposing learners to diverse task versions—enhances generalisation to novel scenarios, even at the cost of slower initial learning. Our digital-twin simulator operationalises this principle by reconstructing anatomically diverse bronchial trees from patient CT data, thereby bridging the gap between simulated and clinical environments. By replicating the core design of the earlier study by Cold *et al*[5] we ensured methodological consistency, allowing robust evaluation of how anatomical diversity in training affects skill acquisition. This approach underscores the translational potential of digital-twin technology while validating prior findings in a new context.

A plateau in the learning curve of bronchoscopy can be reached with at least ten different patients,[19 20] but the same bronchial model trained ten times may not achieve the same results. Classical bronchoscopy simulators typically offer a limited number of cases for training and testing,[7 21] which may be a key factor contributing to the poor performance of participants when tested using the new bronchial tree model after training with traditional simulators. The adaptive expertise approach emphasises deep conceptual understanding by integrating multiple concepts necessary for expertise, the discovery of new solutions through struggle and failure, and the ability to train in a variety of contexts.[19 20] However, our digital twin-based bronchoscopy simulator is pretrained on an extensive CT dataset, allowing it to automatically and accurately reconstruct lung structures, including anatomical variants and lesions, facilitating the generation of a comprehensive bronchial tree model based on patient data. This simulator offers diverse scenarios to replicate realistic clinical environments, such as various anatomical variations and the presence of tumours. Although our study did not directly measure patient-level outcomes, prior systematic reviews suggest that improved procedural adaptability correlates with reduced complications (eg, fewer mucosal injuries during bronchoscopy). Future work should evaluate whether anatomic-variety training translates to measurable clinical benefits, such as shorter PTs or lower rates of diagnostic errors.

Additionally, the simulator-based training group achieved significantly higher scores on the IMI compared with the control group in terms of confidence and overall experience. These findings suggest that the instructional method enhances learners' confidence in performing bronchoscopy and improves their overall learning experience and performance. The goal of learning is not merely to acquire procedural skills but also to work effectively in dynamic and ever-changing environments, which is a defining characteristic of medical practice.[19 22 23] Therefore, approaches that emphasise ability (rather than mere performance), as well as strategies focused on preparing for lifelong learning and developing adaptive expertise, are crucial.

Skill maintenance is crucial for basic clinical skills, particularly during short residency rotations and continuing medical education.[24 25] Nonetheless, high-quality research on this topic remains limited. Previous studies have demonstrated that both low-fidelity 3D-printed airway models and classical high-fidelity bronchoscopy simulators significantly enhance students' bronchoscopy performance and help sustain learning gains when integrated into the curriculum.[26 27] In our study, the digital-twin bronchoscopy simulator also demonstrated superior training outcomes, both immediately following the training and during the retention test conducted 3 months later. The enhanced skill retention and adaptability observed in the anatomic-variety group resonate with Schmidt and Bjork's[18] concept of contextual interference. By training on diverse bronchial models, novices faced increased cognitive demands during practice, requiring them to continuously adapt navigation strategies. This 'desirable difficulty'—though initially slowing skill acquisition—strengthened long-term retention and transferability. Moreover, using the anatomic-uniformity group as a reference, the digital-twin-based bronchoscopy simulator also had better performance in the brand-new digital bronchial tree model test. However, the retention test performance with the digital model revealed a general decline in ability compared with the postsimulation scores; this observation is in line with similar previous reports.[26 27] The implication of these results is that this digital-twin-based bronchoscopy simulator should be considered for trainees who experience a significant gap in exposure to bronchoscopy.

This study has some limitations. First, the accessibility of the equipment is a concern given that it is currently not widely available. This new technology requires continuous improvement to enhance its feasibility for widespread adoption. Second, we reported high retention scores for bronchoscopy performance in the digital-twin simulator group,

表4 基于重复测量的Scheirer-Ray-Hare检验对后测与保留测验数据的统计分析

	试验组间相互作用	群组主效应	试验主效应
使用训练完成的标准数字支气管树模型进行测试			
DC，节段	H=0.233, p=0.89	H=60.62, p<0.001*	H=3.499, p=0.061
SP，进展	H=4.30, p=0.12	H=51.99, p<0.001*	H=20.64, p<0.001*
PT, s	H=7.47, p=0.02*	H=32.36, p<0.001*	H=0.86, p=0.350
使用全新胸部CT生成的数字支气管树进行测试			
DC，节段	H=0.32, p=0.85	H=84.05, p<0.001*	H=4.92, p=0.030*
SP，进展	H=0.24, p=0.89	H=69.62, p<0.001*	H=7.56, p=0.010*
PT, s	H=3.04, p=0.22	H=13.34, p=0.001*	H=0.72, p=0.400

*统计学显著性设定为p<0.05。
DC，诊断完整性；PT，操作时间；SP，结构化进展。

在标准数字支气管树模型测试中，反馈训练在直流电（DC）、标准压力（SP）和压力测试（PT）方面的表现显著优于对照组。与既往研究不同，[5]我们发现使用经典高保真模拟器等标准数字支气管树模型训练的新手，在面对另一种新型数字支气管树模型测试时，其支气管镜操作表现反而有所下降。这些结果表明，经典模拟器的训练效果可能被高估，因为它未必能带来操作表现的稳定性。Schmidt和Bjork [18]的研究证实，通过让学习者接触不同任务版本的多样化练习，即使初期学习速度较慢，也能增强对新场景的泛化能力。我们的数字孪生模拟器通过从患者CT数据重建解剖结构多样的支气管树，将这一原理付诸实践，从而弥合了模拟环境与临床环境之间的差距。通过复制Cold等人 [5]早期研究的核心设计，我们确保了方法学的一致性，从而能够稳健地评估训练中的解剖多样性如何影响技能习得。这种方法强调了数字孪生技术的转化潜力，同时在新背景下验证了先前的研究发现。

支气管镜学习曲线的平台期通常需要至少训练十位不同患者才能达到，[19 20]但同一支气管模型经过十次训练可能仍无法获得相同效果。传统支气管镜模拟器提供的训练和测试案例数量有限，[7 21]这可能是导致参与者在使用传统模拟器训练后，测试新支气管树模型时表现不佳的关键因素。自适应专家方法强调通过整合专业知识所需的多重概念、通过挣扎与失败发现新解决方案、以及在多种情境下进行训练的能力来实现深度概念理解。[19 20]然而，我们基于数字孪生的支气管镜模拟器经过大量CT数据集预训练，能够自动精准重建肺部结构（包括解剖变异和病变），从而基于患者数据生成全面的支气管树模型。该模拟器通过多样化场景模拟真实临床环境，例如不同解剖变异及肿瘤存在情况。尽管本研究未直接测量患者层面的结局指标，但既往系统评价表明，操作适应性提升与并发症减少相关（如支气管镜检查中黏膜损伤减少）。未来研究应评估解剖变异训练是否转化为可测量的临床获益，例如缩短手术时间或降低诊断错误率。

此外，与对照组相比，基于模拟器的培训组在信心和整体体验方面取得了显著更高的IMI评分。这些发现表明，这种教学方法不仅增强了学习者进行支气管镜检查的信心，还提升了他们的整体学习体验和操作表现。学习的目标不仅是掌握操作技能，更重要的是要在动态变化的环境中高效工作——这正是医疗实践的核心特征。[19 22 23]因此，强调能力培养（而非单纯操作表现）的方法，以及注重终身学习准备和适应性专业知识发展的策略至关重要。

基础临床技能的维护至关重要，尤其在短期住院医师轮转和继续医学教育期间。[24 25]然而，关于这一主题的高质量研究仍较为有限。既往研究表明，无论是低保真度的3D打印气道模型还是传统的高保真度支气管镜模拟器，当融入课程体系时，都能显著提升学生支气管镜操作水平并帮助巩固学习成果。[26 27]在我们的研究中，数字孪生支气管镜模拟器同样展现出更优的培训效果——无论是培训后即刻还是三个月后的保留测试中均如此。解剖多样性组观察到的技能保留率提升与适应性增强，与Schmidt和Bjork提出的[18]情境干扰理论相呼应。通过使用多样化支气管模型进行训练，新手在实践过程中面临更高的认知负荷，需要持续调整导航策略。这种“理想难度”——尽管初期会延缓技能习得——反而强化了长期记忆的巩固与技能迁移能力。此外，以解剖学一致性组为参照，基于数字孪生技术的支气管镜模拟器在全新数字支气管树模型测试中表现更优。然而，与模拟后评分相比，数字模型在记忆测试中的表现普遍下降，这一发现与既往类似研究结果一致[26 27]。这些结果表明，对于支气管镜操作经验存在明显不足的培训学员，应考虑采用这种基于数字孪生技术的支气管镜模拟器。

本研究存在若干局限性。首先，鉴于该设备目前尚未广泛普及，其可及性成为关注焦点。这项新技术需要持续改进以提升其广泛应用的可行性。其次，我们报告了数字孪生模拟器组在支气管镜检查操作中具有较高的保留率。

but the retention rates of technical skills remained unclear. In the future, we will explore how frequently or what type of content training must occur to improve the knowledge retention rate. We will also develop a structured training programme. Third, the impact of training on future clinical practice performance is particularly significant.[20 25] Our results suggest that this novel simulator could improve novice bronchoscopy performance (navigation through the bronchial tree and lung segment recognition ability); however, its ability to shorten the learning curve of novices remains unknown. Therefore, this should be explored further in the future. This study focused on simulated performance (Kirkpatrick level 2), but real-world translation requires validation through longitudinal clinical trials.[28] For example, tracking trainees' patient outcomes (level 4) could quantify the simulator's impact on diagnostic accuracy or complication rates. Fourth, while replicating the core design of Cold *et al*[5] strengthened the comparative validity for assessing anatomical diversity, this approach inherently limits the exploration of other potentially influential variables unique to our simulator or training paradigm that might differ from the referenced AI system. Finally, our self-regulated training design, while ecologically valid, introduces variability in skill attainment compared with mastery learning. Systematic reviews[8 29] emphasise that mastery learning—with its emphasis on deliberate practice and objective benchmarks—reduces performance variance and ensures baseline competency.[11] In contrast, our anatomic-variety group's superior retention despite self-paced training suggests that anatomical diversity may partially compensate for unstructured practice, a hypothesis requiring further validation. Future studies should integrate mastery criteria with variable anatomical training to optimise both consistency and adaptability.

CONCLUSIONS

Training with a digital twin simulator enables novices to achieve more structured bronchoscopy performance, as evidenced by superior SP scores.

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Funding This work was supported by the Noncommunicable Chronic Diseases-National Science and Technology Major Project (2024ZD0528900 to G Hou, 2024ZD0528902 to G Hou), CAMS Innovation Fund for Medical Sciences (CIFMS, Grant No. 2024-I2M-ZH-022, 2022-I2M-1-025) and Excellence & Innovation Initiative of China-Japan Friendship Hospital (NO.ZRZC2025-XYA01).

Competing interests GH and MD are the original inventors of the reported bronchoscopy simulator system. This system provides simulated bronchoscopy procedures and airway reconstruction.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants and was conducted from June to July 2024, approved by the ethics committees of all participating centres (China-Japan Friendship Hospital: 2024-KY-095) and written informed consent was obtained from all patients for the designated CT data. Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available on reasonable request.

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但技术技能的留存率仍不明确。未来我们将探索需要以何种频率或内容类型进行培训才能提高知识留存率，并制定结构化培训方案。第三，培训对未来临床实践表现的影响尤为显著。[20] [25]研究结果表明，这种新型模拟器可提升新手支气管镜操作能力（包括支气管树导航和肺段识别能力），但其缩短新手学习曲线的效果尚不明确，需进一步研究。本研究聚焦于模拟操作（柯克帕特里克二级），但实际应用需通过纵向临床试验验证。[28]例如，追踪受训者患者结局（四级）可量化模拟器对诊断准确率或并发症发生率的影响。第四，虽然复现Cold等人[5]的核心设计增强了评估解剖多样性时的比较效度，但这种方法本质上限制了对模拟器或训练范式中其他潜在影响变量的探索，这些变量可能与参考的AI系统存在差异。最后，我们的自我调节训练设计虽然生态效度良好，但与掌握学习相比会引入技能达成的变异性。系统综述[8] [29]强调，掌握学习——通过刻意练习和客观基准来强调——能减少表现差异并确保基线能力。[11]相比之下，尽管采用自主节奏训练，解剖多样性组仍表现出更优的保留率，这表明解剖多样性可能部分补偿了非结构化练习，该假设仍需进一步验证。未来研究应将掌握标准与可变解剖训练相结合，以优化一致性与适应性。

结论

使用数字孪生模拟器进行培训可使新手实现更规范的支气管镜操作，这一点通过更高的SP评分得到证实。

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贡献者FJFH 和GH构思了手稿，并负责概念化和研究设计。MD、FL、FT、C-LT、RT、WC和 ZY 进行了数据库检索和数据提取。MD、WX和WC进行了统计分析。MD、FL、FT、C-LT和 YX 参与了手稿撰写。 ZY 、FW、NZ、SL和 FJFH 参与了研究评估。GH是文章的担保人，对整个工作的完整性负责。所有作者均参与了文章撰写、修订并批准了提交的版本。

资助本研究由非传染性疾病国家重大科技专项（项目编号：2024ZD0528900，资助对象：侯刚；2024ZD0528902，资助对象：侯刚）、CAMS医学科学创新基金（CIFMS，项目编号：2024-I2M-ZH-022、2022-I2M-1-025）以及中日友好医院卓越创新计划（项目编号：ZRZC2025-XYA01）共同资助。

竞争利益GH与MD是所报道支气管镜模拟系统（bronchoscopy simulator system）的原始发明者。该系统可提供模拟支气管镜检查操作及气道重建功能。

患者同意发表不适用。

伦理审批本研究涉及人类受试者，于2024年6月至7月期间开展，已获得所有参与中心伦理委员会的批准（中日友好医院：2024-KY-095），并从所有患者处获取了针对指定CT数据的书面知情同意。受试者在参与研究前已签署知情同意书。

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